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Responses of sub-Saharan smallholders to climate change: Strategies and drivers of adaptation

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ABSTRACT

Rural farm households in sub-Saharan Africa are vulnerable to climate variability due to their limited adaptive capacity. This paper explores how adaptation strategies are adopted by small-holders in sub-Saharan Africa as a function of their adaptive capacity. The latter is characterised by five types of capital: natural, physical, financial, human, and social. We use responses from farm households in sub-Saharan Africa dating from 1536 obtained by Climate Change, Agriculture and Food Security (CCAFS). This data provides information on the adoption of adaptation practices during the study period as well as information with which we develop indicators for the five types of capital. The results suggest that all the five types of capital positively influence adoption of adaptation practices. Human and social capital both displayed a positive and significant effect on the uptake of most adaptation practices. This finding suggests that the effect of less tangible kinds of capital such as knowledge, individual perceptions, farmers' networks and access to information may be stronger than normally assumed. Directing more development policies towards enhancing human and social capital may therefore be more cost-effective than further investments into physical and financial capital, and could help in overcoming social barriers to adaptation to climate change.

1. Introduction

Many farm households in sub-Saharan Africa (SSA) are vulnerable to climate change due to both their strong dependence on agricultural production, and a limited resilience to cope with changing conditions (Schlenker and Lobell, 2010). Moreover, agriculture in rural SSA is the main source of one's livelihood and is the main contributor to GDP. At the same time, agriculture in SSA faces enormous challenges. Firstly, in growing enough food to support the rapidly growing population; in the last two decades the population in SSA has almost doubled (from 0.64 billion in 1998 to 1.05 billion in 2018) and is projected to reach 1.7 billion by 2050 (Livingston et al., 2011). Secondly, there is increasing international pressure to not expand agricultural land at the expense of natural habitats for wildlife. Finally, climate change forecasts predict a decrease in production of between 8–22 percent in key staple crops such as maize, sorghum, groundnut, millet, and cassava by 2050. Predictions were based on various model specifications with a historic time series in the data sources (1961–2000 for NCC or 1961–2002 for CRU 2.1) (Schlenker and Lobell, 2010). These challenges need to be considered when developing policies that increase household food security, reduce poverty, improve livelihoods and facilitate climate change adaptation (Africa Adaptation Programme (AAP), 2013; Beddington et al., 2012; International Fund for Agricultural Development (IFAD), 2013).

Numerous studies in Africa have contributed to understanding how to promote the adoption of adaptation measures at the farm-level (e.g. Below et al., 2012; Bryan et al., 2013; Deressa et al., 2009; Gebrehiwot and van der Veen, 2013; García de Jalón et al., 2016, 2017; Nielsen and Reenberg, 2010; Silvestri et al., 2012). However, most studies evaluate the adaptation process by analysing how socioeconomic characteristics influence adaptation for example, by measuring farm household traits such as education, farm size, ownership, access to credit, and other variables that can be directly observed. Few studies have focused on how the adoption of practices is influenced by the five types of capital: natural, social, physical, financial, and human. This may be due to the fact that these five types of capital are difficult to characterise and quantify.

The five forms of capital are defined as stocks or flows that have the capacity to produce flows of economically desired outputs (Goodwin, 2003). All forms of capital can be seen as indicators of wealth (e.g.

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Lange, 2004; Goodwin, 2003; Figge, 2005) or resilience (e.g. Thornton et al., 2006; Nelson et al., 2005). In addition, they can act as predictors of the uptake of adaptation strategies to climate change (e.g. Wheeler et al., 2013; Below et al., 2012; Iglesias et al., 2011).

Human capital refers to the productive capacities, knowledge, and personal attributes that make an individual more productive (Pindyck and Rubinfeld, 2013). In farming systems, indicators of this capital could be the number of people in the farm-household, education and attitudes towards the environment and climate change.

Social capital consists of trust, understanding and cooperation between individuals and groups (Goodwin, 2003). Thus, the exchange of climate change information between farmers and institutions could be considered indicators of social capital. Indicators of this capital could also include memberships of agricultural associations, the access to information on climate and extreme weather events or the use of social networks (García de Jalón et al., 2018).

Physical capital is formed by manufactured assets generated by applying human productive activities and are used to provide flows of goods and/or services (Goodwin, 2003). It refers to assets such as infrastructure and technology that may improve farm production. Indicators of physical capital in farming systems could include farm assets such as mechanical ploughs, irrigation systems, electronic assets, livestock and land holdings, and agricultural inputs.

Financial capital is related to the capital stock that facilitates economic production. Indicators of this capital could be off-farm and on-farm income, access to credit, having a bank account and remittances.

Natural capital refers to the resources and services of the natural world which yield valuable flows of goods and services into the future (Costanza and Daly, 1992). In farming systems, natural capital is mainly represented by agro-climatic characteristics which predetermine the suitability for agriculture such as climatic (e.g., temperature, precipitation, humidity, solar radiation) and soil (e.g., texture, structure, % organic matter, pH and depth) conditions.

A large body of literature has aimed to study the drivers of adaptation at the farm-household level in SSA (e.g. Deressa et al., 2009; Nielsen and Reenberg, 2010; Silvestri et al., 2012; García de Jalón et al., 2017). The fact that only few studies focused on the effect of the five types of capital could be explained by the difficulty of characterising or quantifying these capitals, a process considerably more complex than measuring farm-household traits such as education, farm size, ownership, access to credit, etc. It is actually possible to include these farm household characteristics within the five types of capital. For instance, education or knowledge about climate change are indicators of human capital. Farm size, machinery and infrastructure are indicators of physical capital. This type of clustering of indicators into the five capitals has been done previously (e.g. Wheeler et al., 2013; Below et al., 2012).

Previous studies have demonstrated that the effect of the five types of capital on adoption, might be different for each adaptation strategy. The study of Wheeler et al. (2013) on Australian farmers showed, that in general, the five capitals positively influenced the adoption of adaptation measures, however, for each particular measure, the influence varied and was even negative in some cases. For example, low education had a positive effect on increasing irrigation area whereas it had a negative effect on changing crop mix. The study of Below et al. (2012) in the Morogoro region of Tanzania, found that some indicators of human and social capital such as education level or female headed households in some cases negatively impacted the adoption of some adaptation strategies. Their study also indicated that physical and financial capital were the greatest predictors for uptake of adaptation measures. Our study extends their research by exploring the influence of the five forms of capital on the adoption of fourteen agricultural practices in nine Sub-Saharan countries. The results may help identify barriers and incentives of adoption across Sub-Saharan smallholders and contribute to better understand how adoption may evolve as farm-household stocks and flows change over time.

Regional scale mathematical models that are spatially explicit and consider land, weather and management characteristics (e.g. partial equilibrium models such as GLOBIOM) can predict the uptake of adaptation strategies over time. However, the actual uptake often turns out to be different from that predicted by the models as some key biophysical and/or socioeconomic characteristics at farm scale are not taken into account. Therefore, a better understanding of the determinants of adoption on the farm scale could ultimately serve to improve the accuracy of such regional scale models.

This paper explores the adoption of fourteen agricultural practices during a 10-year time period in order to better understand farm scale effects. We assess how the adoption of these practices is affected by the five forms of capital at the farm-household level. By taking into account farm-level dynamics the results of this study may contribute to better understand how adoption may evolve in Sub-Saharan Africa.

2. Materials and methods

2.1. Data

This study used three sources of publicly available data: survey data at the household level, social indicators at the district level and climate indicators at the regional level.

Survey data was obtained from the survey of the CGIAR Research program on Climate Change, Agriculture and Food Security (CCAFS) which, was conducted in late 2010 and early 2011 (Kristjanson et al., 2011). The survey was based on face-to-face interviews at the farm-household level and included 1538 farm households in 80 villages as part of 11 case studies across 9 countries (Burkina Faso, Ghana, Mali, Niger, Senegal, Ethiopia, Kenya, Tanzania, and Uganda). The CCAFS survey was designed with the purpose of developing simple and comparable cross-site household-level indicators for which changes in agricultural practices could be evaluated over time (more information available from Kristjanson et al. (2011)).

Additional indicator data to evaluate the natural capital were collected from different data sources. Agro-climatic data was obtained from WorldClim (www.worldclim.org/) and included annual precipitation as well as the difference between precipitation and potential evapotranspiration. This difference between precipitation (water supply) and potential evapotranspiration (water demand) could be used as an indicator of suitability for rain fed agriculture in terms of water availability. The duration of the growing period was obtained from FAO GeoNetwork (www.fao.org/geonetwork/).

2.2. Uptake of the adaptation practices

In this study, the dependent variable is the adoption level of adaptation practices in the farm-households surveyed within the CCAFS research program. Our study assesses the adoption level of fourteen adaptation practices which are classified into six groups: i) Introducing more resistant crop varieties, ii) Introducing or improving irrigation, iii) Improving soil conservation, iv) Introducing integrated pest and crop management v) Increasing the use of fertilisers and agrochemicals and vi) Changing planting and cropping practices.

In the literature, increasing the use of fertilisers and agrochemicals has been previously identified as necessary for sustained agricultural growth in Sub-Saharan Africa (Larson and Frisvold, 1996; Schreinemachers and Tipraqsa, 2012) and considered as an adaptation strategy to climate change since a correct application can enhance water use in water-limited environments (Debaeke and Aboudrare, 2004).

The drivers of adoption of the adaptation practices are classified according to the five kinds of capital: human, social, physical, financial, and natural.

Table 1 shows the selected indicators of the five kinds of capital used to assess adoption. Within human capital, the indicators are education, size of the farm-household, and attitudes towards the

Table 1
Selected indicators of the five kinds of capital used to assess the uptake of climate change adaptation practices in Sub-Saharan Africa in 2000–2010.

Capital	Indicators of capital	Units and Scale	Mean	Std. Dev.	Min	Max
Human	Education	0 = No formal education, 1 = Primary, 2 = Secondary, 3 = Post Secondary	1.23	0.79	0	3
	Household size (number of people)	Number of people	9.12	7.70	1	85
	Changes adopted because less rainfall	1 = Yes, 0 = Otherwise	0.61	0.49	0	1
	Changes adopted because more droughts	1 = Yes, 0 = Otherwise	0.53	0.50	0	1
	Changes adopted because later start of rains	1 = Yes, 0 = Otherwise	0.54	0.50	0	1
Social	Membership in an agricultural group	1 = Yes, 0 = Otherwise	0.32	0.47	0	1
	Access to information about climate extreme events (drought, floods, etc.)	1 = Yes, 0 = Otherwise	0.58	0.50	0	3
	Gender of the household headed	1 = Female headed, 0 = Otherwise	0.16	0.37	0	1
	Ability to access weather forecast 2–3 days	1 = Yes, 0 = Otherwise	0.16	0.37	0	1
	Ability to access information about rain forecast	1 = Yes, 0 = Otherwise	0.41	0.49	0	1
	Ability to access weather forecast 2–3 months	1 = Yes, 0 = Otherwise	0.23	0.42	0	1
	Ability to access information about climate extreme events (drought, floods, etc.)	1 = Yes, 0 = Otherwise	0.34	0.47	0	1
Physical	Owned acreage	Hectares	7.09	15.50	0	300
	Large owned livestock	1 = Yes, 0 = Otherwise	0.56	0.50	0	1
	Having mechanical plough	1 = Yes, 0 = Otherwise	0.23	0.42	0	1
	Having electronic assets in the household (e.g. TV, radio, phone, Internet, computer)	1 = Yes, 0 = Otherwise	0.29	0.17	0	1
	Irrigation systems	1 = Yes, 0 = Otherwise	0.06	0.12	0	0.67
	Household structures (e.g. crop storage facility, concrete and bricks, tap water, etc.)	1 = Yes, 0 = Otherwise	0.18	0.18	0	1
	Separate housing for farm animals	1 = Yes, 0 = Otherwise	0.41	0.49	0	1
Financial	Having a bank account	1 = Yes, 0 = Otherwise	0.09	0.29	0	1
	Access to credit/loan	1 = Yes, 0 = Otherwise	0.13	0.34	0	1
	Receiving remittances	1 = Yes, 0 = Otherwise	0.32	0.47	0	1
	Receiving off-farm paid employment	1 = Yes, 0 = Otherwise	0.19	0.39	0	1
	Receiving cash from fruits	1 = Yes, 0 = Otherwise	0.26	0.44	0	1
	Receiving cash from vegetables	1 = Yes, 0 = Otherwise	0.24	0.43	0	1
	Receiving cash from wood	1 = Yes, 0 = Otherwise	0.08	0.28	0	1
	Receiving cash from large livestock	1 = Yes, 0 = Otherwise	0.27	0.45	0	1
	Receiving cash from small livestock	1 = Yes, 0 = Otherwise	0.64	0.48	0	1
	Receiving cash from livestock products	1 = Yes, 0 = Otherwise	0.33	0.47	0	1
Natural	Annual precipitation	Millimetres	851.7	315.3	438	1384
	Difference between annual precipitation and evapotranspiration	Millimetres	−903.3	494.2	−1962	−216
	Length of growing period	Days	113.6	56.9	50	210

climate change. Personal attributes such as behaviour and values that make an individual more productive are also considered part of human capital (Pindyck and Rubinfeld, 2013). The reason why farmers have adopted changes could reflect in a certain way beliefs in climate change and associated impacts such as changes in rainfall distribution and drought frequency. Thus, they could also be a determinant of adoption of adaptation strategies. For social capital, the indicators are related to membership of agricultural associations, and access and ability to use information on climate conditions and extreme weather events through social networks. Indicators of physical capital in farming systems include farm assets such as mechanical plough, irrigation systems, electronic assets, livestock and land holdings, and agricultural inputs. For financial capital, the indicators are off-farm and on-farm income, access to credit, having a bank account and remittances. Natural capital is represented by annual precipitation, the difference between precipitation and potential evapotranspiration and the duration of the growing period.

2.3. Relevance of the selected indicators

We hypothesise that the five kinds of capital significantly contribute to the uptake of adaptation strategies at the farm household level.

Indicators of human and social capital such as education, values, access and trust towards received information, involvement in local action groups etc. have been shown to reduce social barriers that may currently hinder or limit the adoption of adaptation strategies (Nielsen and Reenberg, 2010; Adger et al., 2009; García de Jalón et al., 2015).

Both physical and financial capital are expected to have stronger effects on the adoption of adaptation measures than the other forms of capital. Both of these forms of capital are indicators of farm-household wealth which has been found to strongly influence adoption of adaptation strategies (Deressa et al., 2009; Bryan et al., 2013).

Natural capital is hypothesised to have both positive and negative effects on the adoption of adaptation. On the one hand, the positive effect on adoption could arise by the fact that farms located in areas more suitable for agriculture are more likely to have more developed farming systems and consequently higher adaptive capacity. On the other hand, farms located in arid and semi-arid regions with a lower natural capital are sometimes projected to suffer stronger climate change impacts and consequently the need of adaptation could be higher. Moreover, adopting some adaptation practices that could enhance farming sustainability (e.g. introducing crop cover, rotations, and intercropping) allows coping with low water availability in water limited environments (Bodner et al., 2007; Debaeke and Aboudrare, 2004). Thus it could be expected that adoption of certain adaptation practices might be higher in drier regions as a result of higher needs for adaptation to climate change.

2.4. Modelling framework

The influence of the five types of capital in 2010 on the uptake of the selected adaptation practices between 2000 and 2010 is assessed with a generalised linear mixed model. The adoption of the practices is treated as a binary dependent variable taking the value of 1 if the given practice is adopted and 0 if not. The five types of capital are the predictors of adoption. In this way, a random intercept Logit model is developed, with random effects for each of the 80 villages.

Eq. (1) describes the random intercept Logit model in terms of a

latent linear response, where only $y_{ij} = I(y_{ij}^* > 0)$ was observed for the latent variable

$$y_{ij}^* = X_{ij}\beta + Z_{ij}U_j + \varepsilon_{ij} \tag{1}$$

Where X_{ij} are the covariates for the fixed effects (i.e. five types of capital) of farm-household *i* in village *j,* with regression coefficients (fixed effects) β. Z_{ij} are the covariates corresponding to the random effects, and could be used to represent both random intercepts and random coefficients. As our case is a random intercept model, Z_{ij} equals the scalar 1. U_j represents the error term for the random effects of the 80 villages which are estimated as variance components. ε_{ij} are the errors following a logistic distribution with mean 0 and variance $\pi^2/3$ and are independent of U_j.

Defining $\pi_{ij} = Prob(adoption_{ij} = 1)$, Eq. (2) indicates the final random intercept Logit model,

$$logit(\pi_{ij}) = \beta_0 + \beta_1 Human_{ij} + \beta_2 Natural_{ij} + \beta_3 Physical_{ij} + \beta_4 Social_{ij} + \beta_5 Financial_{ij} + U_j \tag{2}$$

for $j = 1,\ldots,80$, with $i = 1,\ldots,n_j$ farm-households in village *j* (80 villages).

The model (Eq. (2)) is applied to each of the fourteen adaptation practices.

3. Results

3.1. Uptake of adaptation practices for mitigating impacts of climate change

3.1.1. Uptake of adaptation practices

Firstly, we present descriptive statistics for the uptake of climate change adaptation practices (Table 2). The mean value indicated the adoption rate of adaptation practices between 2000 and 2010 in the farm-households surveyed within the CCAFS program. As shown in Table 2, using manure or compost (57% farm households) and introducing intercropping (55% farm households) were the practices most frequently adopted. On the other hand, introducing crop cover (6% farm households), using integrated crop management (8% farm households) or pest control (7% farm households) and starting irrigation (11% farm households) were the least adopted adaptation practices. Overall, introducing more resistant crop varieties was a relatively widespread group of adaptation practices. 39% of the farm households planted drought tolerant crop varieties in the last 10 years and 24% and 25% planted disease and pest-resistant crop varieties, respectively. Of the farm households surveyed, 11% and 13% introduced micro-catchments and terraces respectively. Finally, 34% of farm households started or increased the use of fertilisers and pesticides and/or herbicides, and 37% of farm households introduced crop rotations.

Table 2
Descriptive statistics of the climate change adaptation practices. All variables are dichotomous (Yes = 1, No = 0).

Climate change adaptation practices (codes)	Mean	SD
Introducing more-resistant crop varieties		
Have you planted drought-tolerant crop varieties in the last 10 years? (drtl)	0.39	0.49
Have you planted disease-resistant crop varieties in the last 10 years? (dstl)	0.24	0.42
Have you planted pest-resistant crop varieties in the last 10 years? (psrs)	0.25	0.43
Introducing or improving irrigation		
Have you started irrigating in the last 10 years? (stir)	0.11	0.31
Improving soil conservation		
Have you introduced micro-catchments in the last 10 years? (mcct)	0.11	0.31
Have you introduced terraces in the last 10 years? (terr)	0.13	0.34
Introducing integrated pest and crop management		
Have you started using integrated pest management in the last 10 years? (umip)	0.07	0.26
Have you started using integrated crop management in the last 10 years? (umcm)	0.08	0.27
Increasing the use of fertilisers and agrochemicals		
Have you started using or using more fertilisers in the last 10 years? (mnft)	0.34	0.47
Have you started using manure/compost in the last 10 years? (mncp)	0.57	0.50
Have you started using or using more pesticides/herbicides in the last 10 years? (umph)	0.34	0.47
Changing practices of planting and cropping systems		
Have you introduced rotations in the last 10 years? (rota)	0.37	0.48
Have you introduced intercropping in the last 10 years? (incr)	0.55	0.50
Have you introduced crop cover in the last 10 years? (crcv)	0.06	0.23

3.1.2. Comparison of country averages

The distribution of the five kinds of capital and the adoption rate in 2000–2010 of the six groups of adaptation practices is presented in Fig. 1. The estimation of the levels of capitals and adoption was based on the different indicators. Since not all observed indicators of capitals had the same measurement scale the values were normalised to a scale from 0 to 1 and averaged for each type of capital. Country estimates were calculated as an average of surveyed farm-households.

Comparing East and West Africa, the uptake of adaptation practices in East Africa seemed to be higher than in West Africa. Overall, the most frequently adopted option was to increase the use of fertilisers and agrochemicals. However, whilst introducing more-resistant varieties was a measure commonly adopted in East Africa, the measure of changing the practices of planting was frequently adopted in West Africa. Moreover, introducing or improving irrigation and introducing integrated pest and crop management turned out to be the least frequently adopted options in both regions.

In general, we find that high values of capital are associated with higher adoption. Thus Ghana, with the highest values for the five types of capital in West Africa also exhibited the highest levels of adoption. Similarly, in East Africa, Kenya and Tanzania exhibited the highest values for capital and for adoption levels. Ethiopia and Niger had the lowest values for capital as well as the lowest adoption levels. Uganda, with the highest value for natural capital, has relatively low adoption levels compared to other countries.

3.1.3. Correlations between countries

We analyse both the correlation matrix of forms of capital (bottom-left values) and of adaptation practices (top-right values) between countries (Table 3). The correlation matrix indicates the similarity of forms of capital and uptake of adaptation practices among countries. The results showed a higher correlation or similarity between neighbouring countries than between distant countries. For instance, Burkina Faso had the highest correlations with neighbouring countries such as Mali, Niger and Ghana. Senegal which among the studied countries only borders onto Mali had very low correlations with the rest of the countries. The correlations with respect to the uptake of adaptation practices were generally lower than for the forms of capital.

3.2. The influence of the five forms of capital on the uptake of adaptation measures

This section describes the results of the mixed logit model assessing the influence of the five types of capital on the uptake of adaptation measures in the last ten years (Table 4).

3.2.1. More resistant crop varieties

Most kinds of capital are found to have a significantly positive effect on introducing more resistant crop varieties. Human and social capital show a positive and significant effect on introducing drought tolerant, disease-resistant and pest-resistant crop varieties. This result is in line with the findings of Abebe et al. (2013), who concluded that both

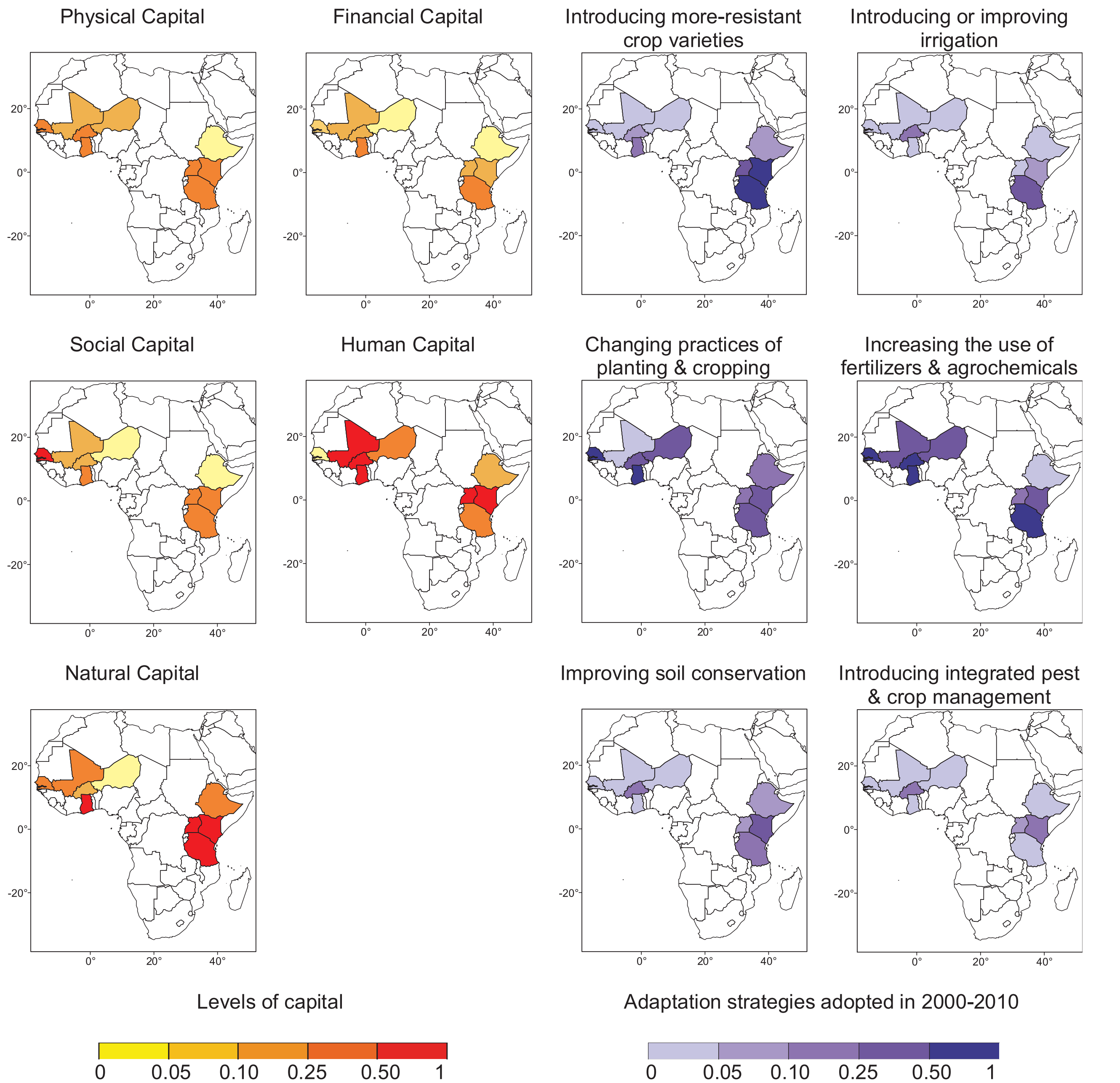

Fig. 1. Distribution of the five kinds of capital and adoption rate of smallholder farm-level adaptation strategies in 2000–2010. Country estimates were calculated as an average of surveyed farm-households.

Table 3
Correlation matrix of forms of capital (bottom-left values) and adaptation practices (top-right values) between countries.

	Burkina Faso	Ethiopia	Ghana	Kenya	Mali	Niger	Senegal	Tanzania	Uganda
Burkina Faso	1	0.364	0.456	0.364	0.602	0.613	-0.122	0.257	0.236
Ethiopia	0.008	1	0.516	0.475	0.529	0.378	-0.051	0.415	0.539
Ghana	-0.030	0.022	1	0.497	0.639	0.455	-0.129	0.409	0.441
Kenya	0.006	0.157	0.160	1	0.572	0.397	0.009	0.372	0.445
Mali	0.183	0.140	0.056	0.170	1	0.624	-0.003	0.446	0.499
Niger	-0.006	0.042	0.016	0.031	0.028	1	-0.060	0.232	0.224
Senegal	0.022	0.002	-0.064	0.013	-0.027	0.073	1	-0.072	-0.034
Tanzania	0.066	-0.015	0.063	0.174	0.041	0.043	0.008	1	0.370
Uganda	0.029	0.095	0.067	0.168	0.104	0.003	-0.016	0.154	1

Forms of capitals (top-right)

Adaptation practices (bottom-left)

Table 4
Estimated coefficients of mixed logistic regressions assessing the uptake of climate change adaptation practices. Number of observations = 1538; Number of groups = 80.

Adaptation measures (codes)	Human	Social	Physical	Financial	Natural	Constant	Random-effects		Wald $chi^2(5)$	$Chibar^2(01)$
							Estimate	Std. Error		
Introducing more-resistant crop varieties										
Drought-tolerant (drtl)	1.37***	0.74***	−0.08	0.33	1.96***	−2.76***	2.02	0.23	69.2***	419.3***
Disease-resistant (dstl)	1.23***	1.15***	0.14	0.74*	3.15***	−4.78***	1.65	0.22	117***	215.9***
Pest-resistant (psrs)	0.81***	1.29***	0.04	0.7*	2.66***	−4.19***	1.63	0.21	114.2***	222.1***
Introducing or improving irrigation										
Irrigation (stir)	0.88**	0.77**	1.2***	0.57	0.85†	−4.62***	1.62	0.24	58.2***	140.8***
Improving soil conservation										
Microcatchments (mcct)	0.62†	0.79**	0.61†	0.78†	0.62	−5.79***	3.02	0.46	28.7***	263.8***
Terraces (terr)	0.55†	0.64*	0.33	0.95†	1.33	−6.62***	4.11	0.59	16.2***	524.6***
Introducing integrated pest and crop management										
Pest management (umip)	0.95*	0.72**	0.55†	0.88*	−1.02†	−4.6***	1.96	0.37	26.7***	88.6***
Crop management (umcm)	1.2***	0.63*	0.39	0.41	0.06	−5.37***	2.35	0.38	23.3***	157.4***
Increasing the use of fertilisers and agrochemicals										
More fertilizers (mnft)	0.73***	0.41*	1.38***	0.4	−0.06	−1.92***	2.06	0.23	62.2***	440.5***
Manure/compost (mncp)	0.77***	0.44*	0.77**	0.63†	−0.34	−0.03	2.00	0.23	37.9***	376.7***
More pesticides (umph)	1.15***	0.98***	1.17***	1.01**	0.32	−2.43***	1.71	0.20	115.1***	273.5***
Changing practices of planting and cropping systems										
Rotations (rota)	0.76***	0.36*	0.61**	0.81**	−0.45	−1.12***	1.67	0.18	44.8***	310.6***
Intercropping (incr)	0.87***	0.44**	0.21	0.5†	0.3	−0.47	1.67	0.18	35.8***	342***
Crop cover (crcv)	−0.57	0.54†	0.18	1.58***	1.61*	−5.14***	2.06	0.37	30.4***	130.3***

† = $p < 0.1$.
* = $p < 0.05$.
** = $p < 0.01$.
*** = $p < 0.001$.

human and social capital are key determinants for the introduction of high-yielding and more resistant crop varieties on African farms. Whilst higher human capital could be linked to greater knowledge about new crop varieties and their potential benefits in a changing climate, higher social capital could be related with better access to seed dealers and to information on climate change. Physical capital, however, does not appear to significantly affect adoption. Therefore, higher knowledge and access to information and seed markets seem to be better predictors of introducing climate resistant crop varieties when compared to farm-household assets. Financial capital is found to significantly impact the introduction of disease and pest-resistant crop varieties. However, in the case of introducing drought-resistant varieties the effect is not statistically significant. Natural capital was found to have the strongest effect in terms of introducing crop varieties which are more resistant to droughts, pests and diseases.

This result differs from our initial hypothesis which assumed that the effect of physical and financial capital would have the strongest effect on adoption of this practice. This might be explained by the fact that the introduction of more resistant varieties might be limited by the access of farmers to improved seeds which could vary among the studied regions (Nordhagen and Pascual, 2013). Farmers who live in regions less suitable for agriculture might not be willing to invest in improved seeds as much as farmers who live in regions with higher natural capital associated to higher returns on investment. Furthermore, since most farms rely on rain-fed agriculture it might be possible that in dry regions farmers were already using drought-tolerant varieties before 2000 and consequently the introduction of new varieties in the period 2000–2010 was rather low.

3.2.2. Irrigation systems

The findings are consistent with the aforementioned hypotheses that all forms of capital are expected to have positive effect on the adoption of irrigation systems. Physical capital is found to be the strongest predictor. This seems reasonable since farm-households with more infrastructure would probably have higher capacity to introduce or improve irrigation systems.

3.2.3. Soil conservation practices

Introducing soil conservation practices such as micro-catchments and terraces is found to be fundamentally driven by social capital. This may be because in SSA the implementation of soil conservation techniques in agriculture has been strongly fostered by agricultural extension services and technical advisors (Rockström et al., 2009). Natural capital is not found to significantly affect the introduction of micro-catchments or terraces. However, it could be expected that in areas with low natural capital, such as water-limited environments, the need to adopt soil conservation practices is higher as it enhances the field capacity of soil, and increases the amount of retained water available for farming (Debaeke and Aboudrare, 2004).

3.2.4. Integrated pest and crop management

Human and social capital are found to have the strongest effect on introducing integrated pest- and crop management. This could be explained by agricultural networks and memberships in farming associations. Within human capital, education and climate change perceptions are found to be relevant determinants of this practice. The negative coefficient of natural capital in introducing integrated pest management indicates that this practice is more frequently adopted in the driest and least suitable agricultural regions. However, this could also be the result of different socio-economic contexts among the case studies. Parsa et al. (2014) found that socio-economic factors such as insufficient training and technical support to farmers, lack of favourable government policies and support and low levels of education are the main obstacles of introducing integrated pest management in developing countries.

3.2.5. Fertilisers and agrochemicals

All kinds of capital are found to have a positive effect on increasing the use of fertilisers and agrochemicals with the exception of natural capital. Natural capital does not show a significant effect which implies

that suitability for agriculture is not related to the use of fertilisers and agrochemicals. Physical capital (farm assets such as machinery and infrastructure) is the strongest predictor of fertiliser and agrochemical use. Social capital is found to have a relatively strong impact on adoption of this practice. This could be explained by the fact that social capital is formed by items related to access to information provided by dealers of fertilisers, agrochemicals or seeds. This finding agrees with Stuart et al. (2014) who pointed out that fertiliser dealers and seed company agronomists are typically one of the most trusted sources of information of farmers.

3.2.6. *Changes in farm-management practices*

All forms of capital, except natural capital, show strong positive effects on introducing crop rotations. Human and social capital seem to be the strongest predictors of introducing intercropping. In the case of introducing crop cover, natural and financial capital show the strongest influence. The positive effect of the natural capital indicates that adoption of these practices is more likely in wetter regions.

4. Discussion

Our results show that between 2000 and 2010 the most frequently adopted adaptation practices in SSA were an increased use of fertilisers and agrochemicals. This observation can be explained in terms of the importance of fertilisers and agrochemicals, which are considered critical for growth productivity in SSA (Schlenker and Lobell, 2010). Adaptation practices such as introducing or improving irrigation systems, which can provide an immediate and effective response to a decrease in water availability, were not widely adopted. Such practices require higher investments and consequently, the financial barrier could hinder potential adoption. Burke et al. (2006) highlighted that, in the past two decades the investment in agricultural irrigation systems in SSA has declined considerably. This decrease could be due to both disappointing returns in response to elevated investments in this technology, and because farms require certain infrastructure and assets to afford irrigation systems. These observations are in line with our results which show that physical capital is the main driver in introducing or improving irrigation systems.

4.1. *Physical capital*

Physical capital is found to be the most powerful predictor of introducing or improving irrigation and of increasing the use of fertilisers and agrochemicals. Therefore, investing in improving farm-household assets such as infrastructure, as well as in inputs for crop production could lead to an increase in the uptake of these climate change adaptation practices. Access to basic needs such as a home with electricity, tap water, improved roofing, etc. could also be important determinants of adoption since they indicate a certain level of household wealth which increases the probability of adoption (Kuntashula et al., 2015; García de Jalón et al., 2017). Thus a straightforward policy recommendation to enhance the adoption rate would be improving basic needs of farm-households. This policy measure aligns with the multitude of development policies (e.g. the Millennium Development Goals) suggested to eradicate extreme poverty (Beddington et al., 2012).

4.2. *Social capital*

Social capital is found to have a positive and significant influence on the uptake of all adaptation practices. This is in line with previous studies that suggest that by investing in social capital, such as access to information, agricultural extension services and farming associations and networks one could obtain an improved uptake of practices (Deressa et al., 2009; Below et al., 2012; Africa Adaptation Programme (AAP), 2013; International Fund for Agricultural Development (IFAD), 2013). Directly investing in improving social capital could contribute to overcoming the cognitive, normative and institutional barriers to adaptation (Jones and Boyd, 2011). These social barriers have been found to considerably hinder the uptake of adaptation, and to be the main cause of the failure for adopting so-called ‘no-regret’ or ‘low-regret’ adaptation options (Nielsen and Reenberg, 2010; Adger et al., 2009).

4.3. *Human capital*

Human capital is found to have a positive and significant influence on the uptake of all adaptation practices with the exception of introducing cover crops. This is in line with previous research that suggest that, education, an indicator of human capital, is an important determinant of farmers’ perception and attitudes towards climate change (García de Jalón et al., 2015; Islam et al., 2013) and of adoption of farm-level adaptation measures (Deressa et al., 2009; Below et al., 2012).

4.4. *Financial capital*

Although not always statistically significant, financial capital has a positive effect on the uptake of all adaptation practices. This indicates that for farm-households with high financial resources the likelihood of adoption was higher. This finding disagrees with García de Jalón et al. (2016) which found that in some cases the adoption of low-regret or no-regret adaptation measures was higher in poor farm-households. This difference could be explained by substitution of adaptation options. For instance, whilst wealthier farm-households have the capacity to introduce an irrigation system to reduce crop water stress, poorer farm-households might select alternative measures such as introducing crop rotations or intercropping to attempt to achieve the same benefits (Bruelle et al., 2017; Bodner et al., 2007; Debaeke and Aboudrare, 2004). Thus, the effect of financial capital could be positive in some practices and negative in others.

4.5. *Natural capital*

Natural capital is found to mainly determine the introduction of resistant crop varieties. One explanation could be that adoption is more likely to take place in humid regions and areas more suitable for agriculture. However, the within country differences among the socio-economic contexts of the case studies such as institutional or normative factors could have stronger effects than the effect of the natural capital on adoption. Thus, the estimated effect of natural capital could be a combination of the natural capital and differences of socio-economic contexts between countries. For instance, access to improved seeds might not vary substantially among farms within the same area but it could vary among countries. This difference among countries can be driven by different socio-economic contexts and this difference can in some cases, be more relevant than the differences in natural capital. Thus, the estimated effects of the natural capital interact with the effect of regional socioeconomic characteristics.

4.6. *Substitution of capital*

The substitution of capital could play a key role in predicting the future adoption of adaptation measures in SSA. It is noteworthy that the estimated effects of the different forms of capital may not be the same in the future or in different socio-economic contexts due to capital substitution (Bowen et al., 2012). The economics literature has widely examined how factors of the production function can be substituted for one another without limiting the capacity of production (Hartwick, 1978; Figge, 2005). With the economic development of farms, the influence on adoption of some factors of production such as knowledge in the labour force, entrepreneurship and technology can increase over time. Thus, it may be argued that with economic development, the

returns to public investment in improving physical capital of farm-households may diminish whereas returns related to other forms of capital such as social and human capital may increase. Moreover, adaptation to climate change could also increase the substitution of capitals (Reed et al., 2013).

5. Conclusions

This study has shown that the use of a mixed logit modelling approach can provide an analytical framework to estimate how the five types of capitals affect the uptake of adaptation strategies. Whilst increasing the use of fertilisers and agrochemicals was widely adopted in 2000–2010, the uptake of introducing irrigation, integrated crop management, and soil conservation practices was rather low. The effect of different forms of capital on adoption varied according to the adaptation practices. Overall, most kinds of capital positively influenced adoption. The results point to the importance of social and human capital. Instead of emphasising development policies that focus on physical assets and financial capital, a lot may be gained by supporting policies that enhance human and social capital.

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